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The Muon System of the CMS Detector at LHC

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1 Introduction

CMS [1] is a detector to be operated at the Large Hadron Collider (LHC). A general overview of the detector was presented at this conference by C. Seez [2]. Here I am going to give some more details on the CMS muon system.

Although "CMS" stands for Compact Muon Solenoid, the detector is capable to measure precisely electrons and photons as well as muons. However, as the name stands, it has been optimized first for measurement of muons. The main reason for this is that many interesting physics processes like the higgs decay H→ZZ→ 4μ, manifest themselves by muons. Muons provide also a good tool to study t and b quark properties, CP violation and heavy ion physics. Moreover they offer an "easy" signature: a single particle in the outside part of the detector.

The muon system is not the only part of the detector used for muon measurements. The inner tracker improves momentum resolution, especially at low momenta. The calorimeters filter other particle types. They are also used to check wether the muon is isolated or associated to a jet. The overall arrangement of all the components is shown in Fig. 1.

2 Magnet

The core of the CMS detector is a large, superconducting solenoidal coil providing a 4T magnetic field. The solenoid is long enough to create a quite uniform field in the whole acceptance region, $|\eta| < 2.5$. The magnetic flux is returned by a saturated iron yoke. The detailed field map is shown in Fig. 2. The main parameters of the magnet are collected in the tables below.

coil length	14.0	m
inner diameter	5.9	m
field inside the coil	4.0	T
field in the yoke	1.8	T
B·R	5.0	T·m
B·R^2	6.2	T·m^2

radial pressure	64	atm
axial force	9900	t
operating current	20	kA
stored energy	3	GJ
iron yoke weight	12000	T
estimated cost (coil+yoke)	120	MCHF

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3 Layout of the muon system

The CMS muon system consist of 4 muon stations interleaved with an iron yoke (see Fig. 1 and 3). The total area of the muon stations exceeds 3000 m^2. Dead spaces are arranged in such a way that every track crosses the sensitive area of at least three stations. Each station is used for triggering as well as for momentum measurement.

4 Momentum measurement

In the solenoidal field of CMS tracks are bent in the $r\varphi$ plane. Hence the precise vertex constraint ($\approx$ 15 μm) can be used. In principle, the muon momentum can be measured in three independent ways:

- sagitta measurement in the inner tracker,
- bending angle measurement right after the coil,
- sagitta measurement in the return yoke.

Obviously, the best resolution is obtained when all the three methods are combined. Furthermore the redundancy of the measurement makes the system robust against various kinds of background. The simulated momentum resolutions of the CMS muon system alone and combined with the inner tracker are presented in Fig. 4.

4.1 Muon chambers

The momentum measurement requires a precise position determination ($\approx 200\mu m$ per measuring plane). Since the expected occupancies and rates are low ($\approx$ 1 Hz/cm^2) drift tubes are natural candidates for muon chambers. Actually two types of chambers are considered: Drift Tubes with Bunch Crossing Capability (DTBX) and Wall-Less Drift Chambers (WLDC). In the very forward region where rates are substantially higher (10-1000 Hz/cm^2) Cathode Strip Chambers (CSC) are foreseen.

4.1.1 Drift Tubes with Bunch Crossing Capability (DTBX)

The DTBX chambers are composed of planes of proportional tubes [3]. Each muon station contains 8 layers measuring the $r\varphi$ coordinate and 4 layers measuring the orthogonal coordinate (see Fig. 5). Each plane consists of independent drift cells, 4×1 cm^2 in size, made of extruded plastic (NORIL).

The electrostatic cell layout is shown in Fig. 6. The central anode wire is at +HV, while C-shaped cathodes at $-$HV are obtained by painting the sides of the cell with graphite or laying copper or aluminium strips during the extrusion process. The central part of the tube remains insulating thus allowing the possibility of measuring the drift time by capacitive coupling with strips parallel to the wires, avoiding decoupling of HV for wires readout. The chamber is designed to be operated in proportional mode with a non-flammable gas mixture.

In order to obtain the time resolution needed to identify the bunch crossing and to generate the first level muon trigger a mean-timer technique is proposed. A detailed description of this method was given at this conference by P. Zotto [4].

The first DTBX prototype has been already tested in the RD5 experiment [5]. The time resolution of 3 ns has been obtained, which corresponds to a space resolution of about 200 μm for a single cell.

4.1.2 Wall-Less Drift Chambers (WLDC)

In this concept [6] each muon station is a rigid monolith made up of 10 layers of fine-grained drift chambers for position measurement and of a twin layer Resistive Plate Chamber (RPC), (see also Section 5.3.1) with square pad electrodes (see Fig. 7). Six drift layers measure the $r\varphi$ coordinate, and four layers measure the orthogonal coordinate. The RPC pads are used for local muon arrival time measurement and for resolution of spatial ambiguities in multitrack events.

The drift chamber is composed of "multicells"; each multicell houses 16 drift cells and consists of two identical profiles about 23 cm wide and 1 cm thick. Existing prototypes are made of aluminium, but for the large scale production, plastic formed by injection in mould or by extrusion are being considered. The individual drift cell is 14 mm wide. The is no wall between them; each cell is separated from its neighbour only by two cathode wires to avoid a dead space. A very thin foil, of about 0.05 mm, would also meet this requirement. The cell covers are shaped to create a sensitive volume of well defined limited thickness (see Fig. 8).

The first prototype has already been tested in the RD5 experiment [7]. The spatial resolution of 200 μm per single cell has been obtained for a 20% CO_2 / 80% Ar mixture.

4.1.3 Cathode Strip Chambers (CSC)

CSC are multiwire proportional chambers with segmented cathode readout. The typical two gap module shown in Fig. 9 consist of a flat, stiff but lightweight panel made as a sandwich of 2.5 mm thick paper honeycomb with two layers of copper-clad glass-epoxy laminates 1.25 mm thick. The cathode pattern is lithographically etched on either side of the panel.

The endcap modules are trapezoidal with radial strips of average pitch of 5 mm. Two anode planes consisting of 30 μm diameter wires spaced at 2.5 mm are placed at a distance of 2.5 mm from either strip cathode. This symmetric cell is optimum for cathode charge interpolation. Finally unsegmented cathodes made also of similar honeycomb panels complete the doublet. Four such modules can form a muon station.

The maximum drift time in a given cell is about 25 ns for a CF_4 / CO_2 mixture at a field of 6 kV/cm. First tests in RD5 indicate a resolution as good as 80 μm per layer [8].

5 Muon trigger

Triggering at LHC is a real challenge. The particle rate varies from 1 up to about 1000 Hz/cm^2 depending on the angle. In total, of the order of 10^{16} pp collisions per year will be seen. On the average 25 pp collisions take place every 25 ns. The first level single muon trigger has to reduce this rate down to about 1 kHz, i.e. six orders of magnitude.

5.1 Physics goals

Three types of the first level muon trigger are considered:

1. **Inclusive single muon trigger**, $|\eta| < 2$, $p_t^{cut} \approx 25 - 100$ GeV
   to study large p_t W physics and search for massive W' at high luminosity (10^{34}cm^{-2}s^{-1}).

2. **Inclusive double muon trigger**, $|\eta| < 2$, $p_t^{cut} \approx 10$ GeV
   this is in fact a Z^0 trigger to be operated at high luminosity (10^{34}cm^{-2}s^{-1}).

3. **Low p_t double muon trigger**, $|\eta| < 2.5$, $p_t^{cut} \approx 4$ GeV
   to be used at low luminosity (10^{33}cm^{-2}s^{-1}) e.g. to study CP violation in b decays.

5.2 Technical requirements

Rate

An original idea of CMS is to abandon the classical three level structure of the trigger system. Usually the second level trigger is made of fast, dedicated (and therefore expensive) processors providing simple arithmetic operations with high performance. Trends in the computer development suggests that in a few years this task can be taken over by cheap, commercial workstations. Thus after the first level trigger data goes to such an "event filter" which is a computer farm performing tasks usually done by the second and the third level trigger. In case of CMS this event filter is designed to operate with up to 50 kHz total first level trigger rate. In fact we estimate that this rate should not exceed 10 kHz, thus a rather large safety margin is assumed. Such a scheme imposes quite high requirements for the first level trigger. For example the single muon trigger rate should be of the order of 1 kHz.

Flexibility

In order to access all the interesting physics channels and to tune the rate to the level acceptable for the event filter the p_t threshold must be adjustable. In the present design the full range 4–100 GeV is covered.

Time resolution

The trigger should be able to assign an event to the proper bunch crossing. Thus the time resolution should be much better than the bunch crossing interval, i.e. 25 ns.

Speed

An answer of the trigger must be available about 2 μs after collision. Taking into account cable length, only $\approx$ 500 ns remain for trigger processor operation.

High acceptance

Searches for rare events require acceptance to be close to 100%. Therefore the muon stations are arranged in such a way that every track crosses at least 3 triggering planes.

Redundancy

The trigger system has to deal properly with all possible inefficiencies, noises, accidental pileups and background from muon radiation. Thus, it has to have a substantial redundancy. In CMS this is ensured by the fact that the measurement is done in at least three detector planes.

5.3 Trigger detectors

A large uncertainty in the estimation of physics rates, background and noise level, as well as the possibility of surprises due to "new physics" forces us to make the trigger system very flexible with a large safety margin. Therefore we are going to build two independent muon trigger systems: one based on the muon chambers like DTBX, WLDC and CSC, and a second one using dedicated fast detectors. For the first solution I refer to the talk of P. Zotto [4] where it is demonstrated how to make drift tubes fast enough to be used in the trigger. Here I will describe some general ideas and give more details about the second solution.

The best candidate for a muon trigger detector seems to be the Resistive Plate Chamber (RPC) [9]. However in the region above $|\eta| = 2$ the particle rate can exceed 100 Hz/cm^2 which is a limit for standard RPCs. Therefore Parallel Plate Chambers (PPC) [10], have been foreseen to cover this region. However recent encouraging results with pure Freon RPCs [11] give a hope that also that region can be accessible for this technique.

5.3.1 Resistive Plate Chambers (RPC)

The RPC consists of two parallel plates, made out from resistive plastic (with resistivity $10^{10} - 10^{12}$ $\Omega\times$cm) separated by a gas gap of a few mm thickness. The outer surfaces of the resistive material are coated with conductive graphite paint to form the HV and ground electrodes. The readout is done by metal cathode strips, placed on outside of the separate plastic foil glued over the conducting surface of the cathode. The whole structure is made gas tight and encased in a Faraday cage of thin metal foil. The RPC detector form a rugged, thin plate.

The main properties of the RPCs, which make them very good candidates for large surface muon trigger chambers, are

- Good time resolution ($\leq$ 5 ns), limited by the signal propagation time along the strips.
- Large signals from m.i.p, allowing simple and cheap analog R/O electronics.
- Construction adapted to the mass production.

Since this technique is relatively new, a lot of R&D activities is currently going on [12, 13]. The main place of these activities is again the RD5 experiment, where many types of RPCs are actually tested (see talk by L. Pontecorvo [14]).

5.3.2 Parallel Plate Chambers (PPC)

The PPC is a single-gap detector with planar electrodes working in the avalanche mode. Individual chambers are small, up to 5$\times$5 cm^2, with a gap of 1-2 mm leading to a very high uniform electric field. A ceramic material, alumina (97% Al_2O_3), has been chosen for the construction of the cells. The surfaces of the electrodes are mechanically polished to a flatness of 5 μm. The machined substrates are then metalized by deposition of 0.5 μm of evaporated chromium. PPC planes of arbitrary shape can be made as a mosaic of cells, each mechanically independent of the other.

PPCs are extensively tested in RD5. The main results were presented at this conference by A. Malinine [15].

5.4 Principle of operation

The solenoidal magnetic field of the CMS detector causes track bending in a plane perpendicular to the beam direction (Fig. 10). In the central part of the detector the magnetic field is almost independent off the z coordinate (along the beam direction). In the forward region the bending power of the solenoidal magnetic field decreases with pseudorapidity η. However the bending is still big enough to distinguish transverse momenta with a wide range of values.

In principle, knowing the vertex, two measuring planes after the coil giving a local track vector are enough to measure the momentum and apply a p_t cut. However in order to deal with fluctuations due to multiple scattering and energy losses we make use of 4 measuring planes (one per station). A four point pattern (Fig. 10) is more redundant than the simple vector and gives a sharper cut.

The above idea has to be modified for muons with $p_t < 6$ GeV in the barrel because they are not able to reach outer muon stations. Therefore we place two RPC planes in the first and the second muon station and again use a four point pattern to make the p_t cut.

5.5 Practical realization

Since the track is bent in the plane perpendicular to the beam it is enough to know precisely only the φ coordinate. Thus a measurement can be done with long strips positioned along the beam in the barrel and radially in the forward region. In the barrel the length of the strips is limited by the signal propagation time. To keep the time resolution below 10 ns the strip length should be of the order of 1 m. In the forward region finer segmentation is required because the bending depends on η and different cuts have to be applied for different η regions.

The width of the strips is determined by the required momentum resolution. In order to have an efficient p_t cut up to 100 GeV the strip width should be of the order of 5 mrad (3 cm at station 3). Cylindrical symmetry of the problem naturally leads to a projective geometry.

5.6 Trigger processor algorithm

A particle passing the detector crosses muon stations, hitting the RPC strips on its way. In the absence of the energy loss and multiple scattering there will be a one to one correspondence between the pattern of hits and the muon transverse momentum. In the real world with energy loss and multiple scattering there is a set of hit patterns (masks) for each value of p_t. The sets of valid mask change with pseudorapidity η. They are practically η independent in the barrel region, but vary in the forward region. The mask sets for two different transverse momenta are ordered i.e. the set for the higher p_t is a subset for the lower p_t. This property allows us to establish the mask set for a given value of the threshold p_t^{cut}. Such a set can be loaded into a trigger processor. Then every observed track pattern is compared with the predefined masks. A track gives a trigger if its pattern belongs to the set of valid masks.

5.7 Simulation results – efficiencies and rates.

The presented algorithm has been simulated in order to calculate efficiency curves and final trigger rates [16]. The GEANT package has been used to track muons with p_t between 3 and 100 GeV through the CMS detector. Multiple scattering, energy loss and production of secondaries has been taken into account.

The efficiency curves as a function of the muon p_t for different values of p_t^{cut} and η are shown in Fig. 11. The p_t spectra of muons from various processes were then convoluted with the efficiency curves. Starting from the inclusive hadron spectrum we have estimated the rate due to punchthrough using GEISHA shower simulation. This has been checked against measurements made in the RD5 experiment. The complete hit pattern in the muon stations was simulated on which the trigger algorithm was then applied.

The resulting integrated trigger rates for various p_t^{cut} values are shown in Fig. 12.

6 R&D

In order to turn ideas into reality an intensive R&D program has already started. Most of the work concentrates around the RD5 experiment [17]. Appart from tests of various detector prototypes its main aim is to study essential topics related to muon detection at LHC like hadronic punchthrough and muon radiation. The RD5 experimental setup is intended to reproduce a slice of the future CMS detector. It consist of two magnets, providing 3T and 1.5 T magnetic fields, beam chambers, silicon strip detectors, sampling calorimeter, muon drift chambers and RPCs. It is planed to replace all the existing detectors with prototypes more and more similar to the final design.

7 Conclusions

In place of a conclusion let me quote the opinion of the LHC Committee about the CMS muon system expressed in a letter from April 15, 1993 addressed to the CMS spokesman:

"The committee appreciates the overall detector concept of CMS, in particular the importance the collaboration has attached to finding a robust muon system with a highly compact design. [...] The muon system is a convincing design offering good momentum resolution and robust identification and triggering performance."

References

[1] *CMS Letter of Intent*, CERN/LHCC 92-3.

[2] C. Seez, *The CMS Detector at LHC*, this conference.

[3] F. Gasparini and P. Zotto, CMS technical note: CMS TN/92-18, April 1992.

[4] P. Zotto, *Bunch Crossing Identification at LHC Using a Mean-timer Technique*, this conference.

[5] M. Andlinger et all., *Bunch Crossing Identification at LHC Using a Mean-timer Technique*, Padova Univ. preprint: DFPD 93/EP/16, submitted to Nuclear Instruments and Methods.

[6] H. Faissner et al., *Modular wall-less driftchamber for muon detection at LHC*, Nucl. Instr. Meth. A 330 (1993), 76-82.

[7] T. Moers, *WLDC test results*, talk given at the RD5 Collaboration Meeting, December 7, 1992.

[8] J. Shank, *CSC test results*, talk given at the RD5 Collaboration Meeting, June 14, 1993.

[9] R. Santonico, R. Cardarelli, Nucl. Instr. Meth. 187 (1981)377,
R. Cardarelli et.al., Nucl. Instr. Meth. A263 (1988) 20.

[10] A. Arefiev et all., *Parallel Plate Chambers: a fast detector for ionizing particles*, submitted to Nucl. Instr. Meth.

[11] R. Cardarelli, *Test of RPC Operating with Pure CF_3Br at RD5*, talk given at the International Workshop on the Resistive Plate Chambers in Particle Physics and Astrophysics, Roma, February 18-19, 1993.

[12] M. Andlinger et all., *Study of Resistive Plate Chambers for moun detection at hadron colliders*, Preprint of "La Sapienza" Roma University, n^o 1015, July 9, 1993.

[13] M. Górski, *Warsaw RPC test results*, talks given at the RD5 Collaboration Meetings, May 27 and June 14, 1993.

[14] L. Pontecorvo, *RPC tests in RD5*, this conference.

[15] A. Malinine, *PPC Technology and Performance*, this conference.

[16] M. Konecki, Warsaw University M.Sc. thesis, 1992, unpublished,
M. Konecki, J. Królikowski, G. Wrochna, *Simulation study of the single muon, RPC based trigger for CMS*, CMS TN/92-39.

[17] *Status Report of the RD5 Experiment*, CERN/DRDC 91-53.